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SATELLITE METEOROLOGY

S. I. Rasool

Institute for Space Studies,
Goddard Space Flight Center, NASA
New York, New York

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How does the sun control the atmosphere of the earth? This question is the starting point for one of the major projects of the United States space program. Its answer may provide an understanding of the basic forces which produce the weather and determine the climate of different regions of the globe.

The significant experiments required for this project are now under way for the first time. Nine Tiros and one Nimbus satellite have been launched by the United States in the past five years. These satellites carry television cameras which yield cloud cover photographs that are producing a substantial improvement in weather forecasting by providing global and nearly continuous coverage of weather activity. Global coverage is critically important, because the success of weather forecasting increases rapidly with the size of the territory covered by the observations.

At the present time large parts of the earth are very poorly covered by weather stations. In these remote areas storms can develop and grow without detection before moving out into the inhabited regions. The sparsely covered areas include the southern oceans, the poles, and the major deserts. Satellite coverage will greatly strengthen the hand of the meteorologist by filling in these blank portions of the weather map.

Many of these 'weather' satellites have also carried infrared radiometers which detect and reveal the pattern of energy distribution in the atmosphere. For the purpose of long-range forecasting, these data are even more important than the cloud cover photographs. We shall discuss separately the more important results so far obtained by the different types of measurements.

Cloud Photographs

The view of the earth from space shows that about 50 percent of the surface of the globe is usually covered with clouds. The formation of clouds over a given region is governed by local meteorological conditions. Low pressure systems are accompanied by intense and widespread cloud cover, while high pressure systems are generally free of clouds. A continuous surveillance by television camera of the cloud cover around the globe, therefore, gives information on the location of large scale weather systems. A global map of cloud distribution is like a weather map plotted by nature. Figure 1 is one such example where several cloud pictures taken by Tiros I over the Pacific have been put together in the form of a mosaic and superimposed on the surface weather map. An excellent agreement between the pressure system and the expected cloud formations is seen. This type of information obtained from the satellite pictures is extremely valuable for operational meteorology.

Cloud photographs of distant parts of the globe are on the desks of meteorologists within two hours of the time they were taken. To date, these photographs have been used to detect, identify and track storms and frontal systems. For example, on April 10, 1960 analysis of photographs from Tiros I enabled the Weather Bureau to give the Australian Meteorological Service the exact location of a typhoon 800 miles east of Brisbane in a region where surface meteorological observations are virtually nonexistent. Tiros II, launched on November 23, 1960, was the first satellite used by the Weather Bureau for routine forecasting operations; in July 1961 Tiros III discovered a hurricane in the Caribbean two days prior to its detection by routine meteorological observations. Tiros III photographed 18 tropical storms in all stages of development.

The TV pictures from the satellites also provide information on the stretches of land covered with ice. Photographs taken by Tiros II clearly showed the breakup of ice packs in the St. Lawrence, thus demonstrating that the weather satellites could also be helpful in navigation by monitoring ice movements.

Cloud photography from satellites has also found its way into areas of fundamental meteorological research. The satellite pictures have shown highly organized cloud patterns, suggesting that certain dynamical mechanisms may be acting to produce these configurations. The most important pattern observed in the cloud pictures is that of cellular-type clouds.

Also, important differences have been found between the laboratory results and those revealed by the Tiros pictures. This is mainly because the actual laboratory experiments are carried out under limiting conditions and are based on theories constrained by questionable assumptions. A study of cloud systems from the Tiros pictures has none of these constraints and can therefore lead us to a better understanding of the dynamics of the atmosphere.

Radiation Measurements

The observations made by radiometers installed in the meteorological satellites are of still greater importance to the basic research in physical meteorology.

The first satellite to carry an experiment of meteorological significance was Explorer VII which was designed to measure the total outgoing radiation from the earth. The results confirmed the expectation that the total radiation emitted by the earth-atmosphere system is correlated with the cloud patterns. Clouds being opaque to radiation of wavelength longer than 3 μ trap the far infrared and, therefore, the emission to space occurs only from the top of the clouds where the temperature is extremely low. The total outgoing radiation is therefore high over clear areas and low for cloudy regions.

Four of the nine satellites in the Tiros series have carried five-channel radiometers with greater resolution than those on Explorer VII. The design of these infrared radiometers has been such as to provide information on the following meteorological parameters:

(1) Mapping the distribution of cloud patterns, both in the day and in the night, and determining the cloud top heights;

(2) Determining the vertical distribution of temperature and possibly the distribution of water vapor in the troposphere;

(3) Determining the global distribution of energy sources and sinks in the earth-atmosphere system, namely the difference between the solar energy absorbed and the infrared energy emitted by the earth and the atmosphere.

The best way to map the clouds by radiometry from a satellite is to "look" at the earth in a spectral interval where the atmosphere is highly transparent and the clouds are completely opaque. This is achieved partly in the 8 - 12 μ interval and to a better degree in the 10 - 11 μ and 3 - 4 μ regions of the infrared spectrum. Up to now, the experiments carried out by Tiros satellites have measured the radiation emitted by the earth in the 8 - 12 μ interval, and have been extensively used to correlate these measurements of the cloud patterns and obtain estimates of the cloud heights.

From Tiros III radiation data, maps of cloud systems associated with Hurricane Anna over the Caribbean were plotted and the storm could be tracked, just on the basis of its radiation pattern, over a distance of more than 4000 km (Figure 2). The height of the cloud tops in the center of the hurricane was found to be about 15 km in contrast to other cloud systems in the vicinity at lower altitudes of 11 to 12 km. Such cloud height differences could not be detected by television cloud photography. Thus radiation in the 8 - 12 μ channel on Tiros has become an excellent tool to map cloud cover and height on a global scale, since this method is independent of illumination by sunlight. This mapping of cloud cover is most effective if the clouds are large enough to fill the field of view of the radiometer uniformly, which is the case for large storms or frontal systems. This method, however, becomes ineffective for the detection of very low clouds or fog where the cloud top temperature is close to the surface temperature.

An analysis of radiation data over a long period of time has indicated that, on an average, the percentage cloudiness may be higher by about 10 - 15 percent over the Southern Hemisphere than in the Northern Hemisphere.

The measurements by Tiros radiometers in the 6.3 μ channel were meant to provide information on the temperature at the tropopause level. Also, because the radiation emitted by the earth's atmosphere in this wavelength region is highly dependent on the amount of water vapor present in the troposphere, the satellite observations have been successfully used to derive the average humidity in the lower atmosphere over selected regions. This method, however, breaks down in the presence of high clouds because the amount of water vapor above a high cloud is so small that no discernible absorption can be measured by the satellite radiometer.

The energy balance of the earth is the other parameter which has been extensively studied by the Tiros radiation data. The energy balance is made up of the difference between the incoming solar radiation, mostly in the visible, and the outgoing terrestrial radiation in the infrared. It is well known that the latitudinal variation of the energy balance shows an excess of incoming solar radiation over outgoing radiation near the equator and a deficiency at the poles. It is this variation of the energy balance with latitude that drives the atmospheric heat engine. Thus, through the determination of the time variations in latitudinal averages of the net energy balance with the aid of the satellite data, one obtains the information which is necessary to understand the general circulation of the atmosphere.

The estimates of the incoming energy from the sun are made by using the satellite observations of the reflected solar energy. The amount of energy absorbed in the earth-atmosphere system is derived from these data by subtracting the reflected energy from the known value of the solar constant calculated for the solar elevation. Tiros IV and VII have given estimates of the reflectivity or "albedo" of the earth for all parts of the globe between 60 ^{o}N and 60 ^{o}S for a period of about a year. The main results obtained from the analysis of the albedo measurements are (a) the total average albedo of the earth for the areas between 60 °N and 60 °S may be about 31 percent; (b) the latitudinal variation in the albedo shows a relative maximum at the equator and a minimum in the two subtropical belts, with the albedo increasing with the latitude up to a value of about 50 percent at 60° latitude. The latitudinal gradient of albedo is found to be steeper than that given by theoretical estimates; and (c) the albedo of the desert regions, namely the Sahara and Arabia, was found to be as high as 45 percent, contrary to the generally believed value of about 25 - 30 percent.

The incoming radiation calculated from these albedo measurements, combined with the outgoing radiation measured by Tiros, then gives the energy balance of the earth-atmosphere system. In Figure 3 we show these values plotted for the whole globe for a period of one year (June 1962 - June 1963), based on the measurements made by Tiros VII. The darkest shade corresponds to a positive energy balance of the order of $+175 \times 10^5$ ergs cm^{-2} sec^{-1}, while the light shades correspond to -165×10^5 ergs cm^{-2} sec^{-1}.

The regions of extreme excesses of radiation balance are situated over oceanic regions and this is mainly because of the fact that the oceans have a large heat capacity and can store a considerable amount of energy. In order to correlate these data with the circulation patterns in the atmosphere, one has to account for the part of this energy that is spent in heating the oceans, land, and the atmosphere, and also the fraction of energy which is in the form of latent heat of water vapor. Such studies have recently been revived because of the availability of new data on the incoming and outgoing radiation from these satellites. It is hoped that a continuous surveillance of the global distribution of energy sources and sinks in the earth-atmosphere system combined with the theoretical studies now underway, would certainly provide a better understanding of the dynamics of the atmosphere.

Future Projects

The meteorological experiments carried out by satellites have so far been limited to broad band radiometry, providing information on the gross features of the thermal structure of the atmosphere. The next step in this field is to make measurements from a satellite by means of an infrared spectrometer. The transmission of infrared radiation in the earth's atmosphere varies considerably with wavelength and altitude. If therefore the satellite measures the energy radiated by the earth in small spectral intervals over the whole infrared region, one can get an estimate of the vertical distribution of temperature. This is the parameter which is the most significant in meteorological research. A spectrometer for this purpose is now being developed which will make observations of the earth in the 15 μ band. In the absence of clouds such measurements may give information on the temperature distribution with altitude in the whole troposphere.

The other spectral region where such measurements may be of great potential importance is the microwave region where the strong absorption by oxygen and ozone is well known. Oxygen has a strong absorption band at 5 mm and this region of the spectrum has been shown to be well suited because detectors of the radiation of this wavelength are available and instrumental techniques have been well established. It has also been suggested that the microwave region can be used to measure the actual ground temperature even in the presence of clouds. This is because the clouds are transparent to longer wavelengths in the microwave region and there is no absorption by any atmospheric constituents. The problem, however, remains that the emissivity of the ground and ocean is not very well known for these wavelengths and varies from region to region. Extensive preparatory measurements from photographs may help resolve this problem.

Another atmospheric parameter which can be usefully observed from the satellite is the distribution of ozone in the stratosphere. Because ozone is a strong absorber of the ultraviolet radiation, the measurements by a satellite of the direct sunlight after its passage through the atmospheric ozone can be used for deduction of ozone distribution in the atmosphere.

The measurement of "sferics", the radiofrequency emissions by lightening, is still another domain in which satellite observation could contribute significantly. The detection and mapping of sferics may indicate areas of strong vertical emission related to tropical storm development and phenomenon like strong winds, heavy rainfall and turbulence. There is a suggestion that a receiver on board a satellite with a large band-pass in the 100 mega-cycles range could be incorporated in the future satellite experiments for this purpose.

It must be mentioned that the most important meteorological parameter, which is the surface pressure and the direction and velocity of wind near the ground, cannot be accurately measured by instruments on board a satellite. The way in which the satellite can contribute to this domain is by acting as a data-relay system. Plans are under way in which the pressure and wind of the lower troposphere would be measured by a series of strategically placed sensors on the ground and in balloons, and the information from these detectors would be transmitted to the over-passing satellite which will relay it to the weather stations.

All these considerations will be part of the future meteorological satellite programs but the implementation is certainly a matter of formidable technological effort and will take at least the remainder of this decade to be completed.

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